THE UNIVERSITY OF UTAH

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March 8, 2001

Mr. Barrett Fountos
U.S. Department of Energy
EH-6/270 CC
19901 Germantown Road
Germantown, MD 20874-1290

Dear Barry:

Two years ago we corresponded about the completion of Milestone 6 of the now-defunct Ukrainian–American Dosimetry Research Project. The article consisting of Milestone 6 had been submitted to *Health Physics* on January 9, 1998 (see attached letters). This article has finally been published, and I am enclosing a copy of the following:

Likhtarev, I. A.; Kovgan, L. N.; Vavilov, S. E.; Perevoznikov, O. N.; Litvinets, L. N.; Anspaugh, L. R.; Jacob, P.; Pröhl, G. Internal exposure from the ingestion of foods contaminated by ^{137}Cs after the Chernobyl accident—Report 2. Ingestion doses of the rural population of Ukraine up to 12 years after the accident (1986–1997). *Health Phys.* **79**:341–357; 2000.

It is, of course, unusual to take this long to get an article published. In this particular case, we had major disagreements with an unknown Associate Editor. And even though major changes were made as requested, the paper was neither accepted nor rejected. Finally, upon appeal to the then Editor-in-Chief, Dr. Kenneth Miller immediately accepted the paper and published it almost verbatim as it was submitted in its final form. The "date stamps" on the published paper indicate that the paper was received on October 15, 1999; actually, this was the date of the appeal to the Editor-in-Chief, not the date of the first submission of the paper (January 9, 1998).

As far as I know, this completes any work stuck in the system related to this old project. We did submit one more joint paper (again with Peter Jacob) on external dose, but this work was initiated and performed after funding was terminated, and the external dose paper will not carry any acknowledgement to the DOE.

In general, I believe this project was very successful. The two published papers on internal dose from radiocesiums are, in my opinion, the most complete documentation of the long-term exposure of the Ukrainian population. The methods and results documented in the two papers are being used by others in continuing epidemiologic research.

Sincerely yours,

Lynn R. Anspaugh, Ph.D.

Enclosures: As noted.

cc: Claudia Beach, w/enc.
Frank Hawkins, w/enc.
Ruth Neta, w/enc.

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January 9, 1998

Dr. Kenneth L. Miller
Editor, *Health Physics* Journal
M.S. Hershey Medical Center
500 University Drive
Hershey, PA 17033

Dear Dr. Miller:

On behalf of Prof. Ilya Likhtarev and other co-authors I am pleased to enclose an original and two copies of the manuscript, "Internal exposure from the ingestion of foods contaminated by ^{137}Cs after the Chernobyl accident. Report 2. General model: Ingestion doses for children and adults of northern oblasts (Kyiv, Zhitomir, and Rivne) of Ukraine, 1986–1996," for your consideration for publication in *Health Physics*.

The first report in this series was published in *Health Physics* **70(3):** 297–317 (1996).

Some of the art work in the enclosed materials is not perfect yet—we will be working on this during the review process. Unfortunately, this is one of the difficulties in working on a multinational collaboration. Prof. Likhtarev is anxious for this paper to be submitted and reviewed while we make minor changes in the graphics.

We believe that our paper is very important in continuing the analysis of what happened following the Chernobyl accident. The mandatory and voluntary countermeasures and the deteriorating socio-economic conditions have clearly impacted the doses received by the population. Also, we feel that our new model is a very practical one and represents an improvement over theoretical ecological models. The model takes advantage of the main types of information likely to be available following any future accident.

Sincerely yours,

Lynn R. Anspaugh

Lynn R. Anspaugh, Ph.D.

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March 24, 1999

Dr. Kenneth L. Miller
Editor, *Health Physics*
M.S. Hershey Medical Center
500 University Drive
Hershey, PA 17033-0850

Dear Dr. Miller:

You will find enclosed a revised manuscript of the paper entitled "Internal Exposure from the Ingestion of Foods Contaminated by ^{137}Cs after the Chernobyl Accident. Report 2. Ingestion Doses of the Rural Population of Ukraine up to 12 Years after the Accident (1986–1997)," by I. A. Likhtarev, L. N. Kovgan, S. E. Vavilov, O. N. Perevoznikov, L. N. Litvinets, L. R. Anspaugh, P. Jacob, and G. Pröhl. An original plus one copy of the complete paper with tables and figures is included. In addition, a diskette is included that contains the text of the paper, appendices, figure legends, and footnotes in one file and the tables in another file. We are also including a version of the old paper marked by Reviewer No. 1. According to your numbering system, this is paper 0023/98.

We have taken all of the reviewers' and Associate Editor's comments into consideration and made changes accordingly. Our quite detailed responses to the 69 questions or comments raised are provided separately. Attached to our responses are the original comments with appropriate numbers applied to both so that they can be matched. A copy of this letter and the detailed responses is also provided.

We appreciate very much the detailed work that has been done by the Reviewers.

Thank you for your indication of interest in our paper.

Sincerely yours,

Lynn R. Anspaugh

Lynn R. Anspaugh, Ph.D.

THE UNIVERSITY OF UTAH

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March 25, 1999

Mr. Barrett Fountos
U.S. Department of Energy
EH-63/270 CC
19901 Germantown Road
Germantown, MD 20874-1290

Dear Barry:

I indicated in my last letter that I was just finishing my part in the revision of the paper representing our old Milestone 6. This revision has now been completed and sent to *Health Physics.* I am enclosing a copy of this paper, which now has a slightly different title:

Likhtarev, I. A.; Kovgan, L. N.; Vavilov, S. E.; Perevoznikov, O. N.; Litvinets, L. N.; Anspaugh, L. R.; Jacob, P.; Pröhl, G. Internal exposure from the ingestion of foods contaminated by ^{137}Cs after the Chernobyl accident. Report 2. Ingestion doses of the rural population of Ukraine up to 12 years after the accident (1986–1997).

I recently participated in a peer review of the studies of the International Consortium for Research on the Health Effects of Radiation, which has major studies ongoing in Russian, Belarus, and Ukraine. I was rather amused that they had no documentation for their dosimetry other than to mention that their Russian thyroid work was "just like" what was published by Gavrilin et al. (the paper I sent you on March 17) and to say that the dosimetry in Ukraine was similar to that of Likhtarev et al. (1996 paper in *Health Phys.*), but would be improved as in the paper just submitted and mentioned above. Thus, I think we have had a positive impact.

Sincerely yours,

Lynn R. Anspaugh, Ph.D.

Enclosure: As noted.
cc: Frank Hawkins, wo/enc.; Elizabeth White, wo/enc.; Ruth Neta, wo/enc.

Paper

INTERNAL EXPOSURE FROM THE INGESTION OF FOODS CONTAMINATED BY ^{137}Cs AFTER THE CHERNOBYL ACCIDENT—REPORT 2. INGESTION DOSES OF THE RURAL POPULATION OF UKRAINE UP TO 12 Y AFTER THE ACCIDENT (1986–1997)

Ilya A. Likhtarev,* Lionella N. Kovgan,* Sergei E. Vavilov,* Oleg N. Perevoznikov,* Leonid N. Litvinets,* Lynn R. Anspaugh,† Peter Jacob,‡ and Gerhard Pröhl‡

Abstract—**Doses from the ingestion of ^{134}Cs and ^{137}Cs during 12 y following the Chernobyl accident have been estimated for approximately 3 million persons living in rural areas of the Zhitomir, Rivne, and Kyiv Oblasts of northern Ukraine. This assessment is based upon an extensive monitoring campaign that provided measurements of ^{137}Cs in more than 120,000 samples of milk and in more than 100,000 persons; such measurements were made in approximately 4,500 locations. Two approaches were used for the dose assessment. In the first approach a so-called reference dose is estimated for each settlement on the basis of measured ^{137}Cs concentration in milk, determination of the milk equivalent of diet, and consumption rates; a further assumption is that a high fraction of the food consumed is produced locally. The reference dose is used as the official dose estimate, which is the basis for any decision on possible financial compensation and economic privileges. In a second step, the so-called real age-dependent dose is estimated from the results of whole body counter measurements and the kinetics of radiocesium in the human body. Real doses above 0.5, 5, and 50 mSv were received by about 40%, 10%, and 0.2%, respectively, of the considered population. With the exception of 1986, for which the monitoring results were limited, the real individual doses derived from whole-body counting are consistently lower than the reference doses. However, this difference declined from a factor of 3–4 in 1987–1989 to a factor of approximately 1.5 in the mid 1990's. The difference between reference and real doses is attributed to the effectiveness of countermeasures implemented after the accident. The effectiveness of these countermeasures decreased with time due to increasing economic problems in Ukraine. The collective reference and real doses of the rural population due to the intake of ^{134}Cs and ^{137}Cs are estimated to be 13,300 and 5,300 person-Sv, respectively. Thus, about 8,000 person-Sv is estimated to have been averted by countermeasures.**

Health Phys. 79(4):341–357; 2000

Key words: ^{137}Cs; Chernobyl; modeling, dose assessment; exposure, population

INTRODUCTION

As a result of the Chernobyl accident, the three largest agricultural oblasts[§] of Zhitomir, Kyiv, and Rivne in Ukraine were contaminated. These territories cover about 80,000 km^2 with a rural population of about 3,250,000 persons living in 4,500 settlements. The radionuclides released during the accident and deposited on the ground result in dose to the population due to external gamma exposure and internal exposure via inhalation and ingestion.

The more important long-lived radionuclides that caused and will continue to cause long-term exposure are ^{137}Cs, ^{134}Cs, ^{90}Sr, and transuranium elements (^{241}Am and $^{238-241}Pu$); the larger contributors to both external and internal dose are the cesium isotopes. These radionuclides contaminated pasture and food crops due to direct deposition on foliage in 1986 and via long-term root uptake in subsequent years.

In accordance with the Ukrainian National Program on mitigation of the consequences of the Chernobyl Accident (Likhtarev et al. 1994; MOC 1992, 1996; POU 1998), extensive radiologic and dosimetric monitoring was provided for the contaminated territories.[‖] In the

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(*Manuscript received* 15 *October* 1999; *accepted* 24 *May* 2000)
0017-9078/00/0

§ An oblast is a political unit similar to a state in the United States. In a previous article (Likhtarev et al. 1996a) somewhat different spellings were used for the three oblasts. This change in preferred spelling is due to changes in the transliteration of names from the Ukrainian (as opposed to the Russian) language.

‖ The main aim of this program was the estimation of doses for the inhabitants of each settlement located in the contaminated areas. These "administrative" doses are one of the main criteria to decide on economic privileges and financial compensation for the population in a settlement.

framework of state monitoring of ^{137}Cs-body burdens up to year 1997, 16,000–30,000 high-quality WBC measurements of ^{137}Cs-body burdens per year were performed in the contaminated areas. For this work a special network system was developed. The structure of this system, the equipment, and the methodology have been described in Likhtarev et al. (1992), Los et al. (1994), and Perevoznikov et al. (1994).

For the estimation of internal doses, the following results of the monitoring campaign in the rural territories are the most important:

- Measurements of ^{137}Cs concentration in milk from privately owned cows (such milk is the main contributor to the daily intake of radiocesium); and
- Measurements of ^{137}Cs-body burdens in members of the public.

These official data are the basis for the model described in this manuscript to estimate exposure and dose due to the intake of radiocesium.[¶] This model is part of the official state methodology (Likhtarev et al. 1996b, 1998) approved by the Ministry of Health and the Ukrainian National Commission on Radiological Protection for the estimation of annual dose and, since 1997, for the calculation of retrospective (for years 1986–1997) and prospective (up to year 2055) doses.

Implementation of this long-term and large-scale program provided the opportunity not only to solve a number of national problems dealing with the Chernobyl accident, but also to store and analyze this unique information concerning the external and internal exposure of millions of persons living on the contaminated territories. In this paper, this experience is generalized regarding the most important and complicated component of exposure, which is the internal exposure from the ingestion of locally produced foods contaminated by radiocesiums.

Two approaches have been developed to estimate doses from the ingestion of radiocesium; these are based on the results of two different types of monitoring:

- Calculation of doses using the relevant models and results of radiocesium concentration measurements in locally produced foodstuffs (mainly in milk). For such estimations here and after the term "reference" is used; and
- Calculation of doses based on direct measurements of body burdens (using the WBCs) among members of the affected population. These estimates (which are called "real") can reasonably be used to make more precise estimates of dose and for verification of the main parameters of the model for "reference" dose.

¶ Throughout this report emphasis is placed on measurements of ^{137}Cs; however, the calculated doses include the contribution of ^{134}Cs.

An important difference between "reference" and "real" estimates is that real estimates are usually lower because direct body-burden measurements reflect the effect of countermeasures and self limitations. Such modifications of traditional diet are not considered in the estimates of reference dose.

Over the long term, mainly two factors determine the levels of radiocesium contamination of locally produced foodstuffs: the ^{137}Cs activity per unit area (σ_0)[#] and the uptake of ^{137}Cs from soil by plants and further transfer to milk and meat. The uptake through roots depends, among other things, on soil type and soil management. As milk is, in general, the main contributor to cesium intake, the aggregated transfer factor from soil-to-milk, k_m^0 (Bq L^{-1} per kBq m^{-2}), is the most important parameter for characterizing the radioecological properties of a specific settlement (Jacob and Likhtarev 1996; Likhtarev et al. 1996a).

The spatial distributions of σ_0, and k_m^0 in the northern part of Ukraine are shown in Figs. 1 and 2. The higher values of σ_0 (up to 400 kBq m^{-2}) are found in the northern part of the Kyiv and Zhitomir Oblasts [the so-called "western footprint" (Izrael et al. 1990)]. Areas with lower values of σ_0 are associated with the "southern footprint" and are found in Kyiv Oblast. Data in Fig. 2 show that even within one oblast the value of k_m^0 can vary by two orders of magnitude. In the northern part of Rivne Oblast there are soils with unusually high values of k_m^0—up to 20–40 Bq L^{-1} per kBq m^{-2}. These "hot spots" occur in areas with marsh-like and acid soils with low content of clay (Jacob and Likhtarev 1996).

When the spatial distributions of σ_0 (Fig. 1) and k_m^0 (Fig. 2) are compared, it is seen that the values of σ_0 in regions with high transfer factors, k_m^0, in Rivne Oblast were, fortunately, much lower than the ^{137}Cs activities per unit area in the northern areas of Zhitomir and Kyiv Oblasts, where the soils are characterized by relatively low values of k_m^0. The transfer factors in the study area are in general higher than the values reported for most soil types in different countries (IAEA 1994).

In Likhtarev et al. (1996a), a model of internal exposure was developed for application to the adult population of Rivne Oblast during the first 6 y after the accident. The aim of this second report is the extension of the model to a longer period of time, a larger geographic area, and to other age groups:

- The 12-y period after the accident (1986–1997) and the territories of the three most affected oblasts of Ukraine are considered;
- The time-dependent ^{137}Cs-milk-concentration function normalized to ^{137}Cs activity per unit area

[#] In order to maintain continuity with Likhtarev et al. (1996a), the authors have used mainly the same designations and definitions of parameters and terms as in Report 1.

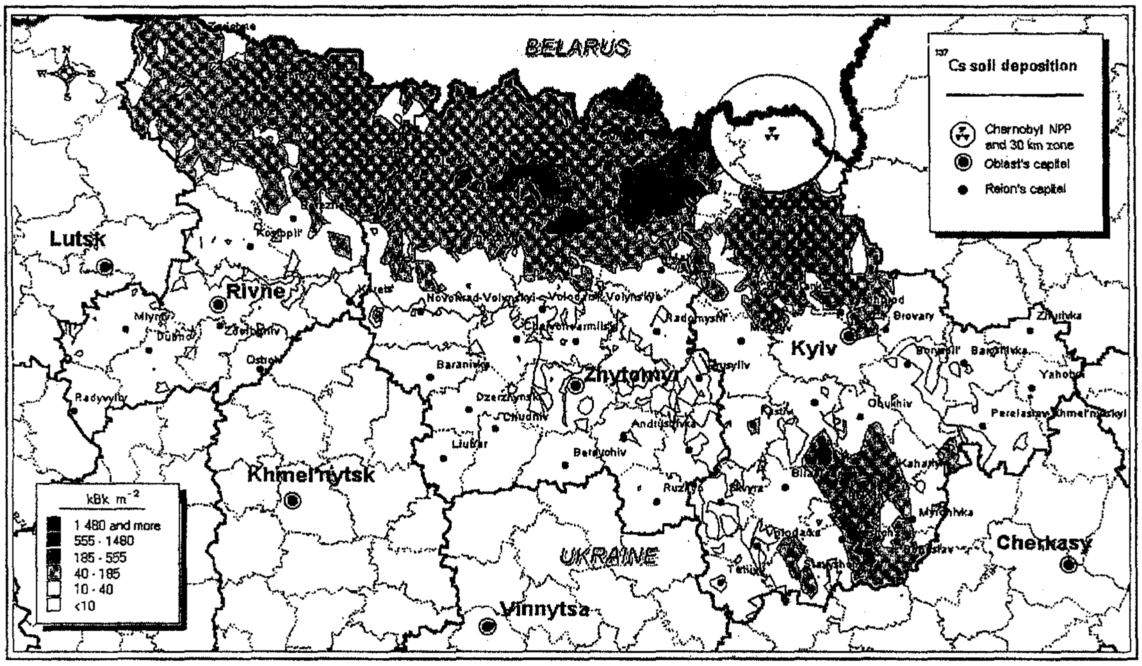

Fig. 1. Map of reference ^{137}Cs activity per unit area, σ_0, in northern Ukraine for the years 1991–1992.

is now defined as a function of two variables, time after accident (t) and k^0_m. Thus, the milk-concentration function is considered to be a generally applicable function and can be applied even for territories with different types of soil;

- Normalized functions for the intake of ^{137}Cs are derived for application to all territories and for the whole time after the accident;
- The annual dose from the ingestion of ^{137}Cs normalized to ^{137}Cs activity per unit area for the years 1986–1997 and the average dose accumulated by the population up to 12 y (1986–1997) for different area of Ukraine are estimated;
- The collective internal doses received by the considered population over the 12-y period are estimated; and

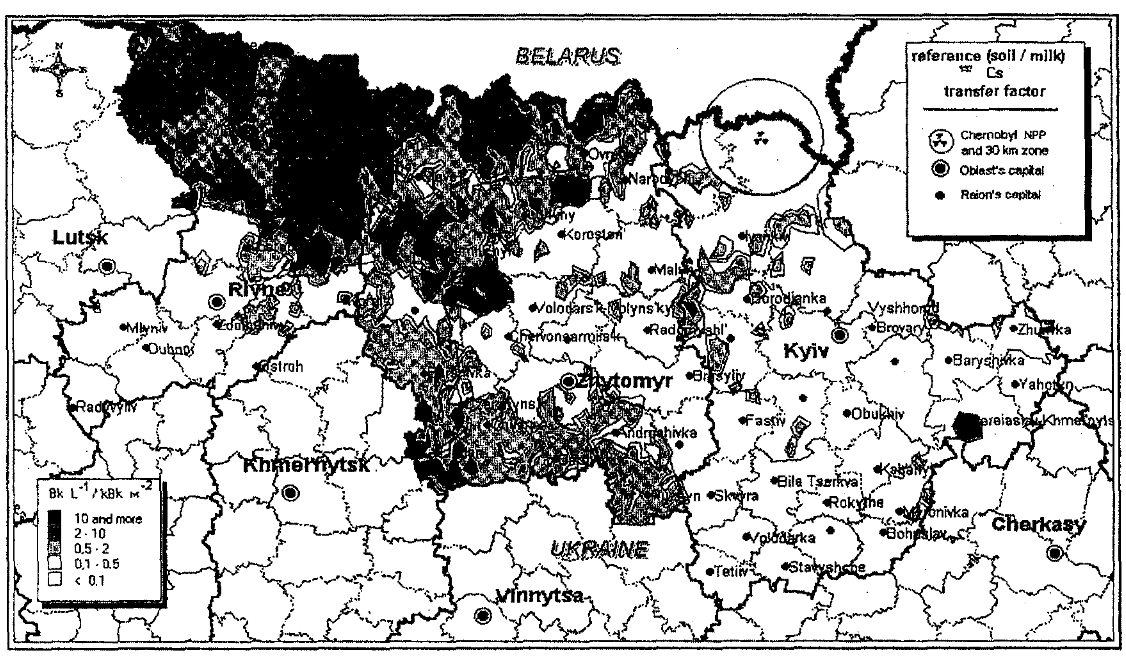

Fig. 2. Map of reference ^{137}Cs soil-to-milk transfer factor, k^0_m, for northern Ukraine.

- The dose effectiveness of countermeasures and the collective dose averted due to countermeasures are estimated.

METHODS: MAIN APPROACHES AND EQUATIONS

A schematic diagram of the methodology used to estimate reference and real doses is given in Fig. 3. In total this scheme contains 16 main compartments, which are combined into two blocks: for estimation of reference dose (upper block) and for real dose (bottom block). Compartments that represent the results of monitoring are also indicated: Compartments 1 and 2 (soil and milk) and Compartment 15 (WBC). Compartment 16 (countermeasure effectiveness) is intended for comparison of the main outputs of the two blocks: estimates of reference and real doses (Compartments 10 and 11), estimates of reference and real intakes (Compartments 9 and 12), and estimates of reference and real milk equivalents (Compartment 8 and 13). Arrows indicate the interconnection of compartments and the order of the calculational procedures.

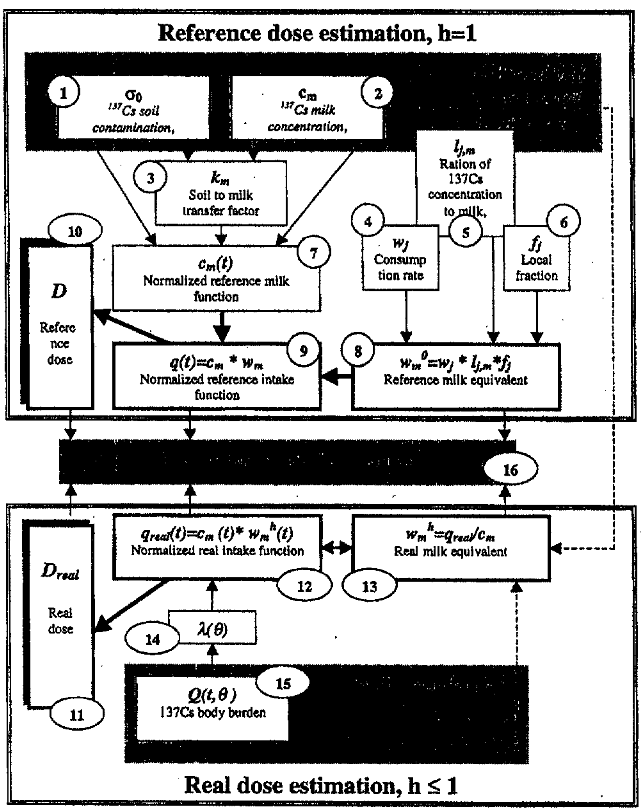

Fig. 3. Structure of the model used to estimate reference and real doses (in the form of compartments).

Reference doses

Reference effective ingestion dose $\tilde{D}^{\tau}$ ** (Sv kBq^{-1} m^{2}) normalized to the ^{137}Cs activity per unit area for time interval τ (Compartment 10) is

$$\tilde{D}^{\tau} = K_{\theta} \cdot \int_{\tau} \tilde{q}(t)dt, \tag{1}$$

where K_{θ} is the effective dose-conversion factor for ^{137}Cs for age θ (Sv Bq^{-1} for ingestion) and $\tilde{q}$ (Bq d^{-1} per kBq m^{-2}) is the reference function of ^{137}Cs intake with diet normalized to the ^{137}Cs activity per unit area (Compartment 9). This function is calculated as the product:

$$\tilde{q}(t) = \tilde{c}_m(t) \times w_m^0(t), \tag{2}$$

where $\tilde{c}(t)$ (Bq L^{-1} per kBq m^{-2}) is the reference-milk function normalized to ^{137}Cs activity per unit area (Compartment 7) and $w_m^0(t)$ (L d^{-1}) is the reference-milk equivalent of diet (Compartment 8), which corresponds to that amount of milk intake (L d^{-1}) that would result in an intake of ^{137}Cs equal to that arising from the consumption of all local foods in diet.

Parameter $w_m^0(t)$ is estimated as:

$$w_m^0(t) = \sum_j l_{j,m}(t) \times f_j(t) \times w_j(t) \times h_j(t), \tag{3}$$

where

$w_j(t)$ = Daily consumption rate of the j-th food product (Compartment 4), kg or L d^{-1};

$l_{j,m}(t)$ = $\tilde{c}_j(t) \times [\tilde{c}_m(t)]^{-1}$ is the ratio of the normalized concentration of ^{137}Cs in food project j-to-the similar concentration in milk (Compartment 5);

m = An index referring to milk;

$f_j(t)$ = Fraction of the daily consumption rate of food j that is produced locally (Compartment 6); and

$h_j(t)$ = Dimensionless food-replacement function that could vary from 0 (complete replacement) to 1 (no replacement).

For reference dose we assume that $h_j = 1$ for all j-food products.

Real doses

The real effective dose (Compartment 11) normalized to the ^{137}Cs activity per unit area, $\tilde{D}^{\tau}_{real}(\theta)$ (Sv per kBq m^{-2}), for time-interval τ and age θ is given by

$$\tilde{D}^{\tau}_{real}(\theta) = K_{\theta} \times \int_{\tau} \tilde{q}_{real}(t, \theta)dt, \tag{4}$$

where $\tilde{q}_{real}(t,\theta)$ (Bq d^{-1} per kBq m^{-2}) is the real intake function of ^{137}Cs with diet normalized to ^{137}Cs activity

** If a function or parameter is normalized to the ^{137}Cs activity per unit area, the symbol "~" is indicated above the parameter.

per unit area (Compartment 12). This function is estimated from the results of WBC-measurements.

The function $\tilde{q}_{real}(t,\theta)$ can be described by the equation:

$$\tilde{q}_{real}(t, \theta) = \lambda_b(\theta) \times \tilde{Q}(t, \theta) + \dot{\tilde{Q}}(t, \theta), \quad (5)$$

where $\tilde{Q}(t,\theta)$ (Bq per kBq m^{-2}) is the normalized ^{137}Cs-body burden at time t for age θ (Compartment 15); $\dot{\tilde{Q}}(t,\theta)$ is the derivative with time of $\tilde{Q}(t,\theta)$; and $\lambda_b(\theta)$ (d^{-1}) is the age-dependent biological elimination rate of ^{137}Cs from the body (Compartment 14).

If the radiocesium intake with diet is constant (during a few months), the real intake, $\tilde{q}_{real}$, (Compartment 12) for age θ can be approximated by a simplified version of eqn (5):

$$\tilde{q}_{real}(t, \theta) = \lambda_{b,i} \times \tilde{Q}(t, \theta), \quad (6)$$

which is true if $\dot{\tilde{Q}}(t, \theta) \approx 0$.

Function $\tilde{q}_{real}(t, \theta)$ can also be written in a form similar to that for function $\tilde{q}(t)$:

$$\tilde{q}_{real}(t, \theta) = \tilde{c}_m(t) \times w_m^h(t) \times \rho(\theta), \quad (7)$$

where $w_m^h(t)$ (L d^{-1}) is the real milk equivalent function (Compartment 13), and $\rho(\theta)$ is an age-dependent modification function (dimensionless).

Effectiveness of countermeasures

The normalized reference dose, $\tilde{D}^\tau$, is based mainly on the results of measurements of radionuclide content in soil and milk, Fig. 3. Such doses were used in Ukraine as the official estimate (so-called "administrative" or "catalog" dose) for a single settlement and were the basis of decisions on the implementation of different types of countermeasures, privileges, and compensations. Therefore, these doses can be conservative. The real dose, $\tilde{D}^\tau_{real}(\theta)$, is considered to be more realistic, as it is based on WBC measurements, and it includes implicitly the time variation of all factors that influence dose, such as countermeasures, self-limitation, and the change in peoples' behavior after the accident. It follows that the dose effectiveness, H^τ_θ, of different countermeasures, actions, and self-limitations for time-interval τ can be quantified as the quotient of the normalized reference dose and the normalized real dose:

$$H^\tau_\theta = \frac{\tilde{D}^\tau}{\tilde{D}^\tau_{real}(\theta)}. \quad (8)$$

Effectiveness of countermeasures can be also estimated as the ratio of reference-to-real intake or the ratio of reference-to-real milk equivalent (Compartment 16).

Normalized reference intake function, $\tilde{q}(t)$

Based on the results of monitoring for each settlement, the two most important radioecological characteristics are estimated:

- The reference-^{137}Cs activity per unit area, σ_0 (kBq m^{-2}), which is the average ^{137}Cs activity per unit area determined from 30–50 samples collected at each settlement in 1991–1992; and
- The normalized reference-transfer factor from soil-to-milk, k_m^0 (Bq L^{-1} per kBq m^{-2}), which is the quotient of the mean ^{137}Cs concentration in milk from privately owned cows collected in the settlement in 1991–1992 and σ_0.

Values determined in the years 1991–1992 are used as the reference, because more monitoring data are available for this period.

Normalized reference milk function, $\tilde{c}_m(t)$

Parameters of function $\tilde{c}_m(t)$. The concentration of ^{137}Cs in milk, c_m, depends on three variables: time t after the accident; ^{137}Cs activity per unit area, σ_0; and properties of soil expressed through k_m^0. With the assumption of a linear dependence of c_m on σ_0 (Compartment 1) and k_m^0 (Compartment 3), this dependence can be expressed in the form:

$$c_m(t, \sigma_0, k_m^0) = \sigma_0 \times k_m^0 \times \tilde{c}_m(t). \quad (9)$$

Further, $c_m(t)$ (dimensionless) can be expressed as a two-component exponential function:

$$c_m(t) = a \times [be^{-\lambda_1 t} + (1 - b) \times e^{-\lambda_2 t}], \quad (10)$$

where a, b, λ_1, and λ_2 are fitted parameters.

From 1986 to 1997, more than 126,000 samples of milk from privately owned cows were gathered from more than 4,400 settlements of Kyiv, Zhitomir, and Rivne Oblasts, and these samples were measured on gamma-spectrometers for ^{137}Cs concentration. The concentration results, normalized to σ_0 and k_m^0, for the settlements of the three oblasts for the years 1987[††]–1997 were combined; a summary of the results is given in Table 1. This data set was then used to estimate the parameters a, b, λ_1, and λ_2 for the normalized milk function $\tilde{c}_m(t)$ [eqn (10)] by the method of maximum likelihood. The estimated parameter values are given in Table 2; values of $\tilde{c}_m(t)$ and the corresponding fitted curve are shown in Fig. 4.

Seasonal variation of ^{137}Cs concentration in milk. Shutov et al. (1993) had reported a seasonal variation in milk from Russian collective farms of about a factor of ten, with the low value occurring in winter. The data collected in Ukraine, which pertained mainly to milk from privately owned cows, were examined for such a seasonal effect. The data are reported in Table 3, and it is clear that there is not a pronounced seasonal variation of ^{137}Cs concentration in milk from privately owned cows. Thus, seasonal variation in function $\tilde{c}_m(t)$ is not considered.

†† Only results of measurements since 1987 were used; during this time period contamination of plants was due to the uptake of cesium from soil via roots.

Table 1. Results of gamma-spectrometry measurements of ^{137}Cs in milk normalized both to reference ^{137}Cs activity per unit area, σ_0, and reference soil-to-milk transfer factor, k_m^0. Measurements were made during 1987–1997 in three oblasts.

Year	Time[a] (d)	Number	GM	GSD (dimensionless)	Year	Time[a] (d)	Number	GM	GSD (dimensionless)
1987	390	63	2.1	2.9	1994	2,843	28	0.3	2.4
	408	53	3.1	2.7		2,976	54	1.2	1.7
	435	58	2.0	3.9		3,001	137	0.6	2.9
	458	43	1.5	3.6		3,020	127	1.3	6.3
	482	49	1.4	3.3		3,037	2,612	0.6	2.7
	505	65	1.0	2.3		3,071	3,705	0.5	3.5
	530	38	0.8	2.5		3,094	3,600	0.6	3.0
	546	6	1.3	2.0		3,112	820	0.3	3.8
	593	64	1.8	4.0		3,134	1,239	0.5	2.7
1988	616	17	1.3	2.8		3,158	2,702	0.6	3.0
	643	9	1.1	5.2	1995	3,291	430	0.5	2.2
	666	44	2.3	3.0		3,307	654	0.4	3.1
	683	20	2.2	2.4		3,322	2,622	0.6	2.6
	701	74	1.5	2.6		3,348	2,982	0.5	3.0
	722	66	1.3	2.6		3,381	2,324	0.5	3.4
	743	47	1.8	3.9		3,407	2,170	0.5	2.9
	770	34	2.0	3.6		3,430	1,272	0.5	3.8
	787	44	1.6	2.4		3,446	2,490	0.3	3.6
	807	62	1.4	2.3		3,463	1,676	0.3	3.5
	827	5	1.0	2.4		3,482	1,596	0.4	2.8
	844	15	1.3	2.2		3,506	204	0.3	5.7
	875	37	1.1	1.8		3,529	81	0.3	3.8
	910	26	1.3	1.8	1996	3,636	115	0.6	1.9
	969	57	0.7	8.2		3,657	1,319	0.7	2.8
1989	1,046	298	2.4	3.3		3,686	1,744	0.6	2.6
	1,074	29	1.7	3.8		3,711	3,296	0.6	3.4
	1,097	36	1.2	5.0		3,733	2,299	0.7	2.9
	1,123	465	2.0	2.4		3,751	1,820	0.6	3.4
	1,147	287	1.7	2.1		3,770	1,264	0.5	3.7
1991	1,923	15,250	1.0	2.6		3,790	880	0.5	4.1
	1,954	1,139	0.9	3.0		3,815	2,169	0.5	3.3
	2,014	260	1.0	2.5		3,835	369	0.5	2.1
	2,070	1,368	1.0	2.1		3,851	46	0.3	2.9
1992	2,108	153	0.8	2.5		3,879	1,704	0.5	3.2
	2,320	3,686	1.0	2.2	1997	3,971	110	0.6	1.7
	2,338	59	0.9	1.9		3,988	75	0.6	1.7
	2,438	89	1.5	2.0		4,005	125	0.5	1.7
1993	2,544	9	0.4	3.2		4,031	691	0.4	2.9
	2,560	30	1.2	1.9		4,049	3,988	0.5	3.6
	2,577	465	0.6	2.6		4,075	3,802	0.5	3.9
	2,594	2,771	0.8	2.7		4,100	367	0.5	1.9
	2,615	2,572	0.8	2.5		4,119	1,379	0.5	3.1
	2,643	662	1.0	2.1		4,139	2,726	0.4	4.2
	2,667	992	0.8	2.7		4,162	1,189	0.7	3.8
	2,695	3,073	0.8	2.9		4,177	1,341	0.4	3.6
	2,714	1,295	0.8	2.8		4,200	822	0.4	4.1
	2,734	402	0.7	2.6		4,219	569	0.4	3.4
	2,762	461	0.9	2.3		4,238	166	0.3	2.7
	2,795	74	0.3	2.3		4,255	401	0.3	2.3

[a] Time in days following the accident on 26 April 1986.

Table 2. The fitted parameters of milk-function, where $\tilde{c}_m(t) = a[be^{-\lambda_1 t} + (1 - b)e^{-\lambda_2 t}]$. Mean is the arithmetic mean and STD is the arithmetic standard deviation.

Parameter	a	b	λ_1 (y^{-1})	λ_2 (y^{-1})	T_1 (y)	T_2 (y)
Mean	3.46	0.9	0.236	0.046	2.94	15.1
STD	0.17	0.04	0.021	0.031	0.26	7.62

Data for ^{137}Cs milk concentration for 1986. Unfortunately, there are only a few measurements of ^{137}Cs in milk for 1986 and in only 19 settlements of Rivne Oblast. For the same time period the data set of WBC measurements is much larger and includes results for all three oblasts. For this reason, the WBC data were mainly used to derive the intake function in 1986. This is described in detail in a following section concerning the analysis of the function, $\tilde{q}_{i,real}(t,\theta)$.

Reference milk-equivalent diet (Compartment 8). Consumption rates of the main food groups for the adult rural population for Ukraine have been given in an official statistical bulletin (MOS 1996) and an official methodological document (MOH 1997). In order to confirm these data and to determine the age-dependent consumption of milk, additional investigations were conducted. In 1991–1992 a special survey of the rural

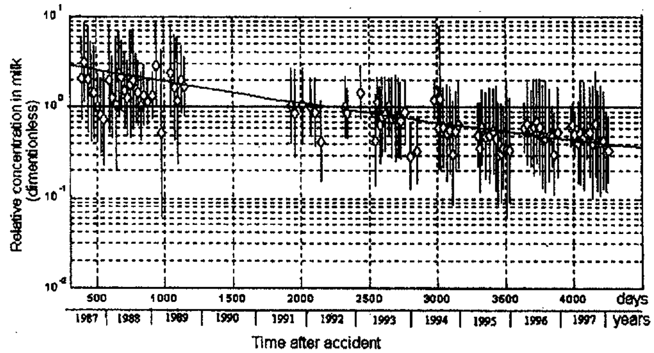

Fig. 4. Results of ^{137}Cs-milk measurements normalized to σ_0 and k_m^0 and the fitted curve $f_m(t) = a[b \times e^{-\lambda_1 t} + (1-b) \times e^{-\lambda_2 t}]$ with parameters from Table 3 generalized for three oblasts in years 1987–1997.

Table 3. Ratio of ^{137}Cs concentration in milk of private cows sampled in winter ($c_{m,win}$)-to-that sampled in summer ($c_{m,sum}$).

Oblasts	No. of settlements	No. of milk measurements		$c_{m,win}/c_{m,sum}$	
		Winter	Summer	GM	GSD
Kyiv	108	7,544	9,085	0.82	2.4
Zhitomir	26	1,044	1,924	1.35	3.2
Rivne	16	240	240	1.15	1.6
Three Oblasts	150	8,828	11,249	0.9	2.5

inhabitants of Kyiv and Zhitomir Oblasts was performed to determine the milk-consumption rates of children and adults (Likhtarev et al. 1996a, b). The results for 3,969 questioned people (1,301 children) are given in Table 4. It is noted that the age dependence of the consumption rate of milk is small and statistically insignificant; consumption varies only from 0.50 to 0.63 L d^{-1}. Based on these results, and because reference doses are considered mainly as doses for use in decision making, the same reference diet (which doesn't change with time) for all age groups of the population is used for all estimates of reference dose.

Table 4. Daily consumption rate of milk for different age groups of the rural population of Ukraine, as estimated from interviews. No. is the number of questionnaires; Mean is the arithmetic mean; and STD is the arithmetic standard deviation.

Age (y)	Daily consumption rate of milk (L d^{-1})					
	Zhitomir Oblast			Kyiv Oblast		
	No.	Mean	STD	No.	Mean	STD
≤2	198	0.57	0.32	20	0.53	0.37
3–4	153	0.50	0.26	23	0.51	0.36
5–7	264	0.53	0.29	32	0.51	0.42
8–11	253	0.53	0.23	123	0.54	0.32
12–15	61	0.52	0.31	102	0.55	0.37
16–17	34	0.51	0.30	38	0.52	0.35
Adults	1,450	0.58	0.38	1218	0.63	0.49

In settlements near forests there is a tradition to consume mushrooms. As this can influence the intake of ^{137}Cs, consumption of mushrooms was taken into account by classifying all settlements according to three categories depending on location. According to consumption-rate data, the daily use of mushrooms is assigned a level of 0.02 kg d^{-1}, but with a weighting coefficient equal to 0 for non-forest settlements located far (>3 km) from forests, 0.5 for settlements for which forests cover ≤ 10% of the area, and 1 for forest settlements.

In Table 5 the value of the reference-milk equivalent, w_m^0, as well as the default values for w_j, f_j, and $l_{j,m}$ are shown. In general, the parameter values in eqn (3) used to estimate reference-milk equivalent can change with time. However, because of the specific use mentioned above for reference dose, the value for w_m^0 was estimated with the following assumptions:

- The reference milk equivalent, w_m^0, has the same value for all population and age groups;
- For the time interval considered, an acceptable approximation for the fraction of local food products is $f_j(t) \approx f_j$ = constant for all j; and
- For all j, the ratio of ^{137}Cs concentration in the j-th product to that in milk, $l_{j,m}$, doesn't change with time: $l_{j,m}(t) \approx l_{j,m}$ = constant.

The last assumption is a simplification and can be valid only for a certain time after the accident. One significant exception to this assumption is for mushrooms; ^{137}Cs in milk decreased significantly with time, whereas the concentration of ^{137}Cs in mushrooms has decreased much less (Jacob and Likhtarev 1996). However, the overall impact of this assumption on the final result is small. The value obtained for the reference-milk equivalent of the

Table 5. Reference-milk equivalent, w_m^0 (L d^{-1}), of diet for rural inhabitants of Ukraine.

Food type	w_j (kg or L d^{-1})	f_j	l_j	$w_j f_j l_j$ (L d^{-1})
Milk and milk products				
Milk	0.640	1	1	0.640
Milk products	0.160	0.6	0.4	0.038
Meat products				
Pork	0.132	1	0.9	0.119
Beef	0.008	0.1	3.5	0.003
Poultry	0.008	1	1.5	0.012
Wild game	0.002	1	9	0.018
Fish	0.020	1	2	0.040
Potatoes	0.360	1	0.13[a]	0.047
Vegetables and fruits				
Vegetables	0.200	1	0.1	0.020
Fruits	0.130	1	0.01	0.001
Leafy vegetables	0.070	1	0.5	0.035
Bread, pasta	0.400	0.01	0.001	0.000
Mushrooms	0.020[b]	0[c]	10	0[c]
Total (kg d^{-1})	2.15			
w_m^0 (L d^{-1})				0.973[c]

[a] For k_m^0 = 1 Bq L^{-1} per kBq m^{-2}.
[b] For "forest" settlements.
[c] For "non forest" settlements.

rural diet is 0.97 L d^{-1}. For "forest" settlements the value of w_m^0 is 1.17 L d^{-1}.

Normalized real intake function, $\tilde{q}_{real}(t,\theta)$

The normalized real intake function, $\tilde{q}_{real}(t,\theta)$, is age-dependent [eqns (4)–(7)] and is determined based on direct body-burden measurements among different age groups of the population. Here, we consider three age groups i: children up to the age of 7 y, children and teenagers of age 8–17 y, and adults aged 18 y and older. The real milk equivalent, $w_{i,m}^h$, of the diet can be also determined from the measurement of $\tilde{Q}_i^{\tau}$ ‡‡ by WBCs for the members of group i at time τ using eqns (6) and (7):

$$w_{i,m}^{h,\tau} = \frac{\lambda_{b,i} \times \tilde{Q}_i^{\tau}}{\tilde{c}_m^{\tau}}. \tag{11}$$

The values of real milk equivalent for age groups i and for years 1986–1997 were derived from the analysis of a large number (about 50,000) of values of $\tilde{Q}_i$, which had been summarized as the average annual values of body burdens for age group i in year τ for a settlement. The results of WBC measurements for more than 1,000 settlements were analyzed.

‡‡ The upper index "t" or "τ" here and later refers to the values of a parameter fixed at time point t (or τ).

For the value of the biological half-life of ^{137}Cs in humans, $T_{b,i} = \ln 2\, \lambda_{b,i}^{-1}$, values of 27.3, 55, and 85 d were applied for the age groups 0–7 y, 8–17 y, and adults, respectively (Lebedev and Yakovlev 1993). These values are different from those recommended in ICRP (1990); use of the locally determined values is preferred here.

Real milk equivalent of diet for different age-groups, $w_{i,m}^h$

In Table 6, values of $w_{i,m}^h$ for the period 1986–1996 are provided for different age groups i in the three oblasts; values of $w_{i,m}^h$ for the period 1991–1996 were calculated by use of eqn (11). In eqn (11) $\tilde{Q}_i^{\tau}$ and $\tilde{c}_m^{\tau}$ correspond to annual values of body burden and ^{137}Cs concentration in milk measured in the same settlement. The real milk equivalents, $w_{i,m}^h$, for the period 1987–1990

Table 6. Calculated absolute values of real milk equivalent of diet, $w_{i,m}^{\tau}$, for three age-groups of Rivne, Kyiv, Zhitomir Oblasts and generalized in 1986–1996. No. is number of WBC measurements in the settlements where ^{137}Cs in milk was also measured.

		$w_{i,m}^{h,\tau}$ (L d^{-1})										
		Rivne Oblast			Kyiv Oblast			Zhitomir Oblast			Three Oblasts	
Year	Age-group (y)	No.	GM	GSD	No.	GM	GSD	No.	GM	GSD	GM	GSD
1986	≤7	36	15	3.89	—	18	6.18	—	27	7.07	20	5.65
	8–17	60	9.3	4.25	—	18	5.44	—	17	7.02	14	5.52
	≥18	311	10.1	3.61	—	15	4.78	—	20	5.79	14	4.70
1987	≤7	83	0.39	4.65	—	0.47	7.16	—	0.68	7.77	0.50	6.46
	8–17	394	0.30	4.33	—	0.57	5.49	—	0.56	6.98	0.46	5.56
	≥18	696	0.29	5.03	—	0.42	6.46	—	0.56	7.52	0.41	6.30
1988	≤7	1,197	0.16	4.76	—	0.20	7.10	—	0.29	7.92	0.21	6.53
	8–17	3,428	0.30	4.75	—	0.57	5.98	—	0.55	7.36	0.45	5.99
	≥18	2,584	0.33	5.45	—	0.47	6.76	—	0.63	7.82	0.46	6.64
1989	≤7	956	0.18	4.80	—	0.22	7.30	—	0.32	7.80	0.23	6.57
	8–17	2,737	0.21	5.15	—	0.40	6.30	—	0.39	8.13	0.32	6.47
	≥18	4,802	0.11	6.21	—	0.16	7.68	—	0.22	8.84	0.16	7.54
1990	≤7	—	0.17	3.45	—	0.22	4.91	—	0.23	4.73	0.20	4.35
	8–17	—	0.19	3.66	—	0.36	4.38	—	0.29	5.21	0.27	4.41
	≥18	—	0.19	4.17	—	0.32	5.11	—	0.23	5.40	0.23	4.88
1991	≤7	395	0.16	2.10	910	0.22	2.51	187	0.14	1.67	0.17	2.11
	8–17	1,082	0.17	2.18	1.708	0.29	2.47	524	0.17	2.30	0.22	2.32
	≥18	1,207	0.28	2.13	1.147	0.49	2.53	1,752	0.24	1.96	0.27	2.21
1992	≤7	89	0.29	1.01	109	0.25	1.42	—	—	—	0.27	1.28
	8–17	231	0.28	1.06	533	0.35	1.60	—	—	—	0.31	1.40
	≥18	49	0.28	1.10	27	0.31	1.80	—	—	—	0.30	1.52
1993	≤7	65	0.27	2.43	77	0.30	6.19	67	0.45	3.75	0.33	4.04
	8–17	461	0.32	1.34	346	0.35	2.28	117	0.42	1.13	0.36	1.67
	≥18	217	0.40	1.39	183	0.78	3.07	421	0.68	1.18	0.60	1.98
1994	≤7	62	0.60	1.21	27	0.50	3.30	184	0.27	2.74	0.49	2.48
	8–17	383	0.61	1.60	—	—	—	816	0.26	2.85	0.40	2.25
	≥18	167	0.69	1.41	511	0.97	2.49	2.498	0.49	2.47	0.69	2.16
1995	≤7	761	0.41	2.36	2.173	0.96	1.28	1.580	0.88	3.22	0.89	2.34
	8–17	3.496	0.45	2.03	3.907	0.98	1.33	12.388	1.09	2.63	0.78	2.04
	≥18	4.905	0.55	1.82	11.660	0.78	1.75	15.910	1.11	2.56	0.78	2.06
1996	≤7	1.226	0.21	2.08	—	—	—	2.414	0.38	3.49	0.28	2.78
	8–17	5.029	0.27	1.90	—	—	—	10.601	0.48	3.62	0.36	2.76
	≥18	12.840	0.34	1.84	—	—	—	20.310	0.76	3.06	0.51	2.46

were estimated with a special procedure (described in the Appendix) because data on the concentration of ^{137}Cs in milk for 1986–1990 are incomplete.

Real milk equivalent for 1986. Direct deposition of radionuclides on the foliage of plants was the main food-contamination process in 1986; the uptake of radionuclides from soil via roots was of minor importance until the end of summer 1986. Therefore, to estimate $w^{h}_{i,m}$ in 1986, results of milk and WBC measurements were not normalized to the values of k^{0}_{m}, because milk contamination in 1986 was determined mainly by the level of ^{137}Cs deposition on soil (and plants).

It is remarkable that the real milk equivalents in 1986 (Table 6) are much higher than in subsequent years. In 1986, all plants already growing at the time of the accident were affected by foliar contamination, and foodstuffs other than milk were a more important source of ^{137}Cs intake. The situation in 1986 was that, because such large territories were contaminated and such a large number of people were affected, the main attention and monitoring activities were focused on areas with very high (>600 kBq m^{-2}) ^{137}Cs activities per unit area (during 1986–1987 nearly the entire population living in such areas was relocated). Thus, in 1986, organized large-scale countermeasures were not applied in the less contaminated areas, especially in rural settlements. It is thus assumed that the reference and the real milk equivalent values were not different in 1986.

Age-dependent modification function, $\rho(\theta)$

According to eqn (6) an age dependence of $\tilde{q}_{i,real}$ is expected and described by function $\rho(\theta)$. In order to consider in more detail the dependence of $\tilde{q}_{i,real}$ on age, the results of direct WBC measurements for children and adults in the same settlements at the same time have been analyzed. The ratio, ρ_i, of radiocesium intake estimated based on body-burden measurements for children of group i to that for adults was considered:

$$\rho_i = \frac{Q_i(\theta < 18) \times \lambda_{b,i}}{Q_{ad} \times \lambda_{b,ad}}, \tag{12}$$

where ad is an index for adults.

In Table 7, the results for the assessment of ρ_i are provided for six age groups according to rural consumption habits during 1986–1996. Statistical analysis of the results given in Table 7 indicates that ρ_i did not change much over time. Thus, it is possible to combine all results for 1986–1996 into one data set; the results are shown in the last row of Table 7. It follows from these combined data that, in general, the intake of ^{137}Cs by children is 10–30% less than for adults during the entire period after the accident. The age dependence of the intake is approximated empirically by the linear function:

$$\rho(\theta) = 0.02\theta + 0.6, \text{ for } \theta < 18. \tag{13}$$

Change in real milk equivalent with time

Although there are differences among the oblasts in the values of $w^{h\tau}_{i,m}$ (Table 6), these differences, as was the case for age dependencies, are not statistically significant (according to χ^2-test criteria), due to the large variability of the data. Thus, the values of $w^{h\tau}_{i,m}$ from the three oblasts in each year were combined in order to reveal the general trends of variation of $w^{h\tau}_{i,m}$ with time in the entire contaminated territory. These results are also shown in Table 6 and plotted in Fig. 5 for the years 1987–1996; some trends of $w^{h}_{m}(t)$ are obvious:

- During 1987–1991, the real milk equivalent decreased by about 40%;
- There is a broad minimum of $w^{h}_{m}(t)$ 4 to 6 y after the accident (1990–1993); and
- From 1991–1996, values of the real milk equivalent returned to the levels of 1987.

A credible explanation of such behavior of $w^{h}_{m}(t)$ with time is as follows. The initial decrease of $w^{h}_{m}(t)$ during

Table 7. Ratio of radiocesium intake rate, ρ_i, with diet for different age groups of children to that for adults in 1986–1996. Calculations are based on WBC measurements for rural inhabitants who lived in the same settlements of Kyiv, Zhitomir, and Rivne Oblasts. STD is the standard deviation and No. is the number of WBC measurements.

	Age group for children (y)																	
	≤2			3–4			5–7			8–11			12–15			16–17		
Year	No.	ρ_i	STD	No.	ρ_i	STD	No.	ρ_i	STD	No.	ρ_i	STD	No.	ρ_i	STD	No.	ρ_i	STD
1986	110	1.18	1.09	222	1.53	1.51	618	1.04	0.70	1,110	0.95	0.63	1,297	0.99	0.59	326	1.45	0.87
1987	—	—	—	38	4.33	5.77	224	1.23	0.53	552	1.19	0.42	644	1.31	0.49	181	1.34	0.64
1988	—	—	—	215	0.5	0.36	719	0.66	0.38	1,805	0.71	0.37	1,459	0.91	0.30	347	1.13	0.41
1989	28	0.98	0.65	344	0.98	0.45	763	0.83	0.42	1,649	0.83	0.41	1,734	0.98	0.45	440	1.39	0.86
1990	20	1.05	0.66	230	1.81	1.58	428	1.51	1.26	548	1.13	0.83	483	0.85	0.48	128	0.98	0.38
1991	—	—	—	54	0.67	0.22	222	0.61	0.13	360	0.71	0.17	375	0.91	0.21	57	0.85	0.19
1992	—	—	—	19	0.49	0.41	209	0.69	0.26	352	0.72	0.35	287	1.16	0.33	36	1.19	0.11
1993	—	—	—	19	0.72	0.19	103	0.82	0.36	521	0.79	0.14	399	0.91	0.19	51	1.23	0.14
1994	—	—	—	183	1.06	0.76	538	1.03	0.65	1,191	0.90	0.35	1,164	1.01	0.26	201	1.05	0.33
1995	30	0.64	0.46	160	0.67	0.29	865	0.74	0.37	2,887	0.82	0.38	3,635	1.03	0.37	1,118	1.36	1.01
1996	77	0.71	0.4	232	0.61	0.27	559	0.68	0.24	1,303	0.72	0.21	1,618	0.86	0.21	615	1.09	0.26
1986–1996	265	0.7	2.55	1716	0.76	2.18	5,248	0.73	1.85	12,278	0.74	1.65	13,095	0.91	1.53	3,500	1.12	1.59

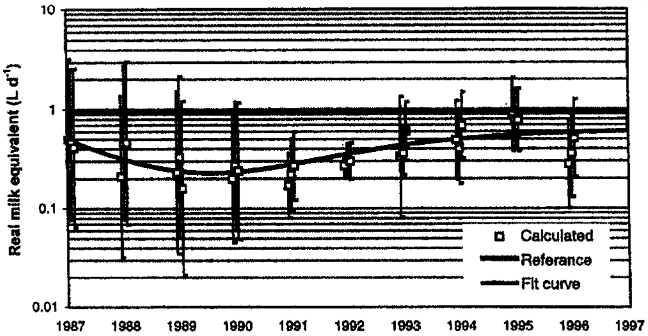

Fig. 5. Calculated values of real milk equivalent, $w_{t,m}^{h,T}$, generalized for three oblasts. The fitted curve is $w_m^h(t)=A_1\ e^{-L_1t}+A_2/(1+A_3\ e^{-L_2t})$ in 1987–1996.

1987–1991 resulted mainly from intensive countermeasures to replace local contaminated agricultural products; people also provided their own self-imposed countermeasures. As time progressed, two other processes tended to increase the intake of ^{137}Cs. The first was the loss of the fear of radiation, which led to decreased self limitation on the use of local food products. The second factor was the decreased ability of the government to implement countermeasures, especially in the rural areas of the country, due to deterioration of the economy. A result was that the diet of the rural population increasingly included more available and less expensive food products produced locally or gathered in the forest.

The following empirical equation was assumed for the description of these very complicated processes:

$$w_m^h(t) = A_1 e^{-L_1 t} + \frac{A_2}{1 + A_3 e^{-L_2 t}}. \qquad (14)$$

In order to obtain numerical values for the parameters A_1, A_2, A_3, L_1, and L_2 in eqn (14), a procedure of non-linear approximation of the values of $w_m^h(t)$ from Table 6 (combined data) was used. The results are given in Table 8 and the fitted curve is shown in Fig. 5.

Normalized values of reference and real intake for 1986–1997

In Table 9, estimates of the annual normalized reference and real (for adults) ^{137}Cs intakes are presented. The values of real milk equivalent, used for calculation of $\tilde{q}^T_{ad,real}(t)$ are also given in Table 9. In Fig. 6 the functions $\tilde{q}(t)$ and $\tilde{q}_{real}(t)$ (for adults) are plotted.

Table 8. Parameters of the function $w_m^h(t)$, where $w_m^h(t) = A_1 e^{-L_1 t} + A_2/(1 + A_3 e^{-L_2 t})$; STD is arithmetic standard deviation.

Parameter	Mean	STD
A_1	0.46	0.11
A_2	0.63	0.20
A_3	20	57
L_1	0.57	0.54
L_2	0.61	0.58

RESULTS: ESTIMATES OF DOSE AND COLLECTIVE DOSE

Normalized reference and real doses from radiocesium ($^{134}Cs + ^{137}Cs$)

So far emphasis has been placed on ^{137}Cs, but ^{134}Cs was also released by the accident; the ratio of ^{134}Cs to ^{137}Cs at the time of accident is estimated to be 0.5. As the radioecological characteristics of these two radionuclides are identical, relationships for ^{137}Cs, corrected to the different physical half-life (2.06 y) of ^{134}Cs, can be used to estimate the intake of ^{134}Cs with diet.

Age-dependent effective dose coefficient K_θ. As discussed above, the biological half-life of ^{137}Cs estimated from WBC measurements in adults is $T_{b,ad} = 85$ d. The effective dose coefficient corresponding to this biological half life is 1×10^{-8} Sv Bq^{-1}, and a similar effective dose coefficient for ^{134}Cs is 1.4×10^{-8} Sv Bq^{-1}.

Annual average normalized reference and real doses from cesium ($^{134}Cs + ^{137}Cs$). In Table 9 estimates on the basis of eqns (1) and (4) are presented for the annual average normalized reference and normalized real effective doses for adults due to the intake of ^{134}Cs and ^{137}Cs.

Dose effectiveness of countermeasures. The results for the effectiveness of countermeasures in 1986–1996 for adults are given in Table 9, as estimated from eqn (8). The effectiveness varies from year to year and decreases with time after 1988. This reflects, as discussed above, the unstable socioeconomic situation in Ukraine and the population's changing perception of the risk of the consumption of local foods.

Average ingestion doses for inhabitants of the three oblasts accumulated up to 12 y after the accident (1986–1997)

Reference and real doses were estimated for 4,227 rural settlements of the three oblasts; the population considered is about 0.877 million in Zhitomir Oblast, 1.28 million in Kyiv Oblast, and 0.752 million in Rivne Oblast. In Table 10 the distributions of population and settlements for the interval of average internal dose accumulated over 12 y are presented.

The following conclusions can be drawn from the results in Table 10:

- Most members of the rural population received relatively low real doses (doses of less than 5 mSv in 12 y were received by 92% of the population in Zhitomir Oblast, more than 97% in Kyiv Oblast, and more than 78% in Rivne Oblast);
- Real doses above 20 mSv are estimated for about 1% of the population in the three oblasts (from 0.52% in Zhitomir Oblast to 1.7% in Rivne Oblast); and

Table 9. Values of annual "reference" and "real" (for adults) ^{137}Cs intake and annual "reference" and "real" effective doses from the ingestion of radiocesium ($^{137}Cs + ^{134}Cs$) normalized to ^{137}Cs activity per unit area in 1986–1997 for areas with $k_m^0 = 1$ Bq L^{-1} per kBq m^{-2}. The corresponding values of real milk equivalent are also shown.

	^{137}Cs intake				Milk equivalent	Normalized dose				Dose effectiveness (dimensionless)	
	Reference		Real		Real	Reference		Real			
	(Bq d^{-1} per kBq m^{-2})				(L d^{-1})	(μSv y^{-1} per kBq m^{-2})					
Year	GM	GSD	GM	GSD	$w_m^h(t)$	GM	GSD	GM	GSD	GM	GSD
1986	2.1	8.00	2.1	8.00	14	9.4	8.0	9.4	8.0	1.0	21
1987	2.2	1.09	1.1	1.54	0.48	15	1.1	4.4	1.6	3.3	1.7
1988	1.8	1.10	0.59	1.77	0.32	10	1.1	2.5	1.8	4.2	1.8
1989	1.5	1.12	0.37	1.88	0.25	7.9	1.1	2.0	2.0	3.9	2.0
1990	1.2	1.14	0.29	2.06	0.24	6.1	1.1	1.9	2.1	3.3	2.1
1991	1.0	1.15	0.29	2.18	0.28	4.8	1.2	1.9	2.2	2.6	2.2
1992	0.84	1.18	0.31	2.32	0.35	3.9	1.2	1.7	2.2	2.2	2.2
1993	0.70	1.20	0.31	2.35	0.43	3.1	1.2	1.6	2.2	1.9	2.2
1994	0.60	1.22	0.32	2.44	0.51	2.5	1.2	1.5	2.2	1.7	2.2
1995	0.51	1.24	0.29	2.46	0.56	2.1	1.2	1.3	2.2	1.6	2.2
1996	0.44	1.28	0.28	2.44	0.60	1.9	1.3	1.1	2.1	1.6	2.2
1997	0.39	1.24	0.25	2.45	0.62	1.6	1.3	1.0	2.1	—	—

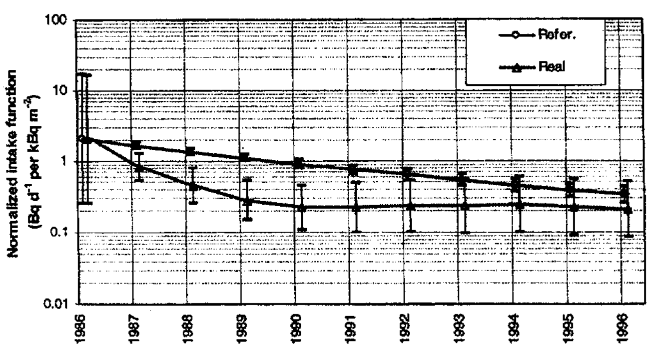

Fig. 6. Time variation of normalized reference, $\tilde{q}(t)$, and real, $\tilde{q}_{real}(t)$, intake functions.

- Real doses exceed 20 mSv in 66 settlements; reference doses above 20 mSv are estimated for 283 settlements.

Collective effective doses from ingestion accumulated up to 12 y after accident

Based on the average values given in Table 10, the collective effective dose of this population from the ingestion of foods contaminated by ^{134}Cs and ^{137}Cs can be estimated. The distributions of the total collective dose and the number of persons in each interval of dose are given in Table 11. (In Table 11a these distributions are given in absolute values, in Table 11b in relative values.) According to Table 11 and the histograms of Fig. 7, much of the population received doses of less than 0.5 mSv, 36% for reference doses and 60% for real doses. About 12% of the population is estimated to have received reference doses between 10 and 100 mSv; for real doses the comparable number is 3%. This underscores the differences of the distributions of reference and real collective doses. The larger amount of reference collective dose accrued to those in the 20 to 50 mSv dose range; the larger amount of real collective dose accrued to those in the 5 to 10 mSv dose range.

Collective dose effectiveness of countermeasures

As discussed earlier, the dose effectiveness of countermeasures is quantified as the ratio of reference dose-to-real dose [eqn (7) and Table 11]. This consideration can also be applied to collective doses. Then, the effectiveness of countermeasures is estimated as the ratio of the reference collective dose to the real collective dose. The collective dose averted by different countermeasures can also be calculated. Estimates of collective dose countermeasure efficiency and averted collective dose for the time interval 12 y after accident for the three oblasts are given in Table 12. The total 12-y collective dose averted by countermeasures is estimated to be 8,000 person-Sv.

DISCUSSION

The contamination from the Chernobyl accident produced an unprecedented radiological problem, where millions of persons living on hundreds of thousands of square kilometers were exposed to significant amounts of radiation. Early attention was focused on assaying thyroid dose, which is not discussed in this paper, and on evacuating or relocating persons living in the more highly contaminated areas. Decision making regarding evacuation or relocation was typically based upon the ^{137}Cs activity per unit area, which could be inferred from measurements of external gamma-exposure rate.

Following resolution of the more urgent issues, attention turned to the much larger problem in terms of scale and time of protecting and monitoring the millions of persons still living in the areas of lesser contamination. Requirements were to assess dose from both external

Table 10. Distribution of population and settlements for the indicated intervals of average reference and real accumulated 12-y dose (1986–1997) for three oblasts of Ukraine.

	Reference ^{137}Cs and ^{134}Cs internal dose															
	Zhitomir Oblast				Kyiv Oblast				Rivne Oblast				Three Oblasts			
Dose range	Population		Settlements		Population		Settlements		Population		Settlements		Population		Settlements	
(mSv)	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
<0.5	358,360	40.8	514	28.7	495,900	38.7	552	39.4	249,520	33.2	418	38.4	1,103,770	37.9	1,484	34.7
0.5–1	210,850	24.0	476	26.6	382,360	29.8	322	23.0	140,570	18.7	257	23.6	733,780	25.2	1,055	24.7
1–2	59,160	6.7	165	9.2	194,120	15.1	215	15.3	24,080	3.20	46	4.2	277,360	9.50	426	10.0
2–5	74,820	8.5	195	10.9	142,030	11.1	183	13.1	25,310	3.40	22	2.0	242,150	8.30	400	9.4
5–10	78,800	9.0	144	8.1	47,360	3.7	71	5.1	75,830	10.10	95	8.7	210,990	6.90	310	7.2
10–20	60,820	6.9	175	9.8	6,170	0.50	20	1.4	111,280	14.80	124	11.4	178,270	6.10	319	7.5
20–50	26,850	3.1	93	5.2	8,530	0.70	20	1.4	98,980	13.20	97	8.9	134,350	4.60	210	4.9
50–100	7,160	0.8	21	1.2	3,890	0.30	10	0.70	24,060	3.20	24	2.2	35,120	1.20	55	1.3
100–150	510	0.06	5	0.3	2,380	0.20	8	0.60	1,960	0.30	5	0.50	4,850	0.20	18	0.40
Total	877,320	100	1,788	100	1,282,730	100	1,401	100	751,590	100	1,088	100	2,911,640	100	4,277	100
	Real ^{137}Cs and ^{134}Cs internal dose															
	Zhitomir Oblast				Kyiv Oblast				Rivne Oblast				Three Oblasts			
Dose range	Population		Settlements		Population		Settlements		Population		Settlements		Population		Settlements	
(mSv)	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
<0.5	574,730	65.5	995	55.6	809,980	63.1	810	57.8	399,290	53.1	692	63.6	1,783,910	61.3	2,497	58.4
0.5–1	59,530	6.8	153	8.6	231,700	18.1	225	16.1	16,980	2.3	34	3.1	308,210	10.6	412	9.6
1–2	64,090	7.3	159	8.9	130,760	10.2	177	12.6	36,660	4.9	20	1.8	231,520	8.0	356	8.3
2–5	108,280	12.3	257	14.4	73,020	5.7	129	9.20	135,110	18.0	168	15.4	316,420	10.9	554	13.0
5–10	53,160	6.1	145	8.1	22,720	1.8	23	1.60	111,830	14.9	114	10.5	187,700	6.4	282	6.6
10–20	12,830	1.5	58	3.2	2,690	0.20	10	0.70	38,750	5.2	42	3.9	54,270	1.9	110	2.6
20–50	4,510	0.50	20	1.1	7,860	0.60	16	1.10	12,720	1.7	17	1.6	25,080	0.90	53	1.2
50–100	200	0.02	1	0.06	2,210	0.20	5	0.40	260	0.03	1	0.09	2,660	0.09	7	0.20
100–150	0	0.00	0	0.00	1,880	0.10	6	0.40	0	0.00	0	0.00	1,880	0.06	6	0.10
Total	877,320	100	1,788	100	1,282,730	100	1,401	100	751,590	100	1,088	100	2,911,640	100	4,277	100

exposure and the ingestion of contaminated foods; only the latter problem is discussed in this paper.

An extensive radiological and dosimetric monitoring program was implemented in Ukraine after the accident within the framework of an Integrated State Program of Dosimetric "Passportization" of the settlements. The more useful measurements for estimating dose from the ingestion of ^{137}Cs were the measurements of the concentration of ^{137}Cs in milk and of body burdens of ^{137}Cs. On the basis of this experience and the large amount of data accumulated over a 6-y period, a phenomenological model (Likhtarev et al. 1996a) of dose from ingestion of radiocesium was developed; the model is expanded in this paper on the basis of data accumulated over a 12-y period. Because the developed model is normalized on the two critical factors (the ^{137}Cs activity per unit area, σ_0, and the soil-to-milk transfer factor, k_m^0), the model is considered to be universal in its application.

Due to its focus on widely available monitoring measurements, the model developed in this paper can be applied to areas of any size for which monitoring results are available; these may be large territories or single settlements. In fact, if large territories and millions of people are considered, it is impossible to take detailed radioecological processes into account. For application over large areas a global model, such as described here, is necessary. The drawback of such a global model is the loss of precise details.

For the northern oblasts of Ukraine it is estimated that about 90% of the collective dose from ingestion arises from the consumption of privately produced milk. No seasonal variations in the concentration of ^{137}Cs in milk were observed, as was indicated in Table 3. This is in marked contrast with the observations by Shutov et al. (1993), who reported seasonal variations of the concentration of ^{137}Cs in milk from collective farms in Bryansk Oblast, Russia, during 1986–1991. The concentration of ^{137}Cs in milk during winter was regularly about a factor of ten lower than in summer; this is due to the availability of relatively uncontaminated feed to collective farms during winter. As such seasonal variations are not observed in the private sector, seasonal variations of ^{137}Cs in milk are not important for dose estimation. Instead preference has been given to the use of integrative concepts, of which one of the more important is the ^{137}Cs body burden, $Q(t,\theta)$, that effectively integrates the daily intake function, $\tilde{q}_{real}(t)$. Another important integrative characteristic is the milk equivalent of diet. This generalized parameter of daily intake smooths the details of consumption rates of different foods and the ratios of

Table 11. Absolute (a) and percentage (b) distributions of the population and the total reference and real collective doses from ingestion of $^{134+137}Cs$ accumulated 12 y after the accident according to intervals of average dose.

a) Absolute distribution

Dose interval (mSv)	Zhitomir Oblast				Kyiv Oblast				Rivne Oblast				Three Oblasts			
	Reference dose		Real dose		Reference dose		Real dose		Reference dose		Real dose		Reference dose		Real dose	
	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)	Coll. dose (person-Sv)	Person (No.)
<0.5	119.2	327,350	124.2	573,860	130.6	473,310	207.4	778,360	88.63	244,420	87.78	393,670	338.4	1,045,070	419.4	1,745,900
0.5–1	144.9	239,370	32.90	45,140	254.2	359,650	175.7	255,220	94.52	141,160	14.32	22,590	493.7	740,170	222.9	322,940
1–2	87.82	60,080	97.99	69,720	288.2	226,810	189.4	136,990	37.95	28,370	61.21	36,660	413.9	315,260	348.6	243,370
2–5	240.1	76,400	366.6	117,160	459.9	150,680	208.3	73,950	90.42	22,230	477.2	134,170	790.5	249,310	1052	325,280
5–10	530.5	78,800	369.2	53,770	357.4	51,320	178.8	23,580	598.9	76,610	792.7	111,630	1487	206,730	1341	188,980
10–20	857.0	60,820	194.1	12,980	88.57	5,610	38.05	2,690	1558	113,790	536.9	39,890	2503	180,220	769.0	55,560
20–50	794.6	26,850	130.1	4,510	329.9	9,090	259.2	7,860	2698	98,980	326.7	12,710	3823	134,910	716.0	25,080
50–100	471.5	7,160	12.83	200	276.2	3,890	130.8	2,210	1570	24,060	13.79	260	2317	35,120	157.4	2,660
100–150	76.01	510	0.00	0	806.2	2,380	303.1	1,880	272.3	1,960	0.00	0	1155	4,850	303.1	1,880
Total	3,322	877,320	1,328	877,320	2991	1,282,730	1,691	1,282,730	7,009	751,590	2310	751,590	13,322	2,911,640	5,329	2,911,640

b) Relative distribution

Dose intervals	Zhitomir Oblast				Kyiv Oblast				Rivne Oblast				Three Oblasts			
	Reference dose		Real dose		Reference dose		Real dose		Reference dose		Real dose		Reference dose		Real dose	
	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)	Col. dose (%)	Population (%)
<0.5	3.6	37.3	9.4	65.4	4.4	36.9	12.3	60.7	1.3	32.5	3.8	52.4	2.5	35.9	7.9	60.0
0.5–1	4.4	27.3	2.5	5.1	8.5	28.0	10.4	19.9	1.3	18.8	0.6	3.0	3.7	25.4	4.2	11.1
1–2	2.6	6.8	7.4	7.9	9.6	17.7	11.2	10.7	0.5	3.8	2.6	4.9	3.1	10.8	6.5	8.4
2–5	7.2	8.7	27.6	13.4	15.4	11.7	12.3	5.8	1.3	3.0	20.7	17.9	5.9	8.6	19.7	11.2
5–10	16.0	9.0	27.8	6.1	11.9	4.0	10.6	1.8	8.5	10.2	34.3	14.9	11.2	7.1	25.2	6.5
10–20	25.8	6.9	14.6	1.5	3.0	0.4	2.3	0.2	22.2	15.1	23.2	5.3	18.8	6.2	14.4	1.9
20–50	23.9	3.1	9.8	0.5	11.0	0.7	15.3	0.6	38.5	13.2	14.1	1.7	28.7	4.6	13.4	0.9
50–100	14.2	0.8	1.0	0.0	9.2	0.3	7.7	0.2	22.4	3.2	0.6	0.0	17.4	1.2	3.0	0.1
100–150	2.3	0.1	0.0	0.0	27.0	0.2	17.9	0.1	3.9	0.3	0.0	0.0	8.7	0.2	5.7	0.1
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

concentration of ^{137}Cs in other foods-to-milk; the advantage of its use is that the milk-equivalent function reflects better the evolution with time of $\bar{q}_{real}(t)$ for large territories and populations.

The calculations of dose presented in this paper have utilized two independent approaches. The first is the estimation of "reference" doses derived from food-consumption rates and results of extensive monitoring of ^{137}Cs concentration in foods; the second is the estimation of "real" doses derived mainly from WBC measurements of ^{137}Cs body burdens. This provides a reliable opportunity to estimate the overall impact of countermeasures quantified as the ratio of reference-to-real doses. This methodology avoids the difficult and speculative estimation of the impact of single mitigating actions in evaluating the effectiveness of countermeasures. Further, the credibility of the results is enhanced if independent approaches are used to assess the same quantity.

The age-dependence of the ingestion doses estimated here is not pronounced. In general, the lowest real doses are estimated for the age group <7 y. However, this age dependence is a minor factor compared to the overall variation in the results.

Although milk is the main contributor to dose, the time dependence of the ^{137}Cs whole body burdens was found to be different from the time dependence of ^{137}Cs in milk. Whereas the ^{137}Cs activities in milk declined continuously from 1986 to 1997, the whole body burdens decreased only during the first 3–4 y and then increased through 1997. This effect was due to the decreasing intensity of countermeasures caused by increasing economic problems in Ukraine. This observation is an important example of the interaction of the socioeconomic conditions and the radiological consequences of the Chernobyl accident.

Although the model is based on the results of extensive monitoring, uncertainties remain. The geographic area considered covers a wide range of soil types and ^{137}Cs activities per unit area. Therefore, the variations of the measured ^{137}Cs activities in milk and humans are quite large; as these are the primary inputs for the model, these variations lead to large variations in the results. Further, the amount of supporting data varies through time and for the three oblasts. The uncertainty of the estimated dose for 1986 is larger than for the other years due to the contribution of foliar deposition to the

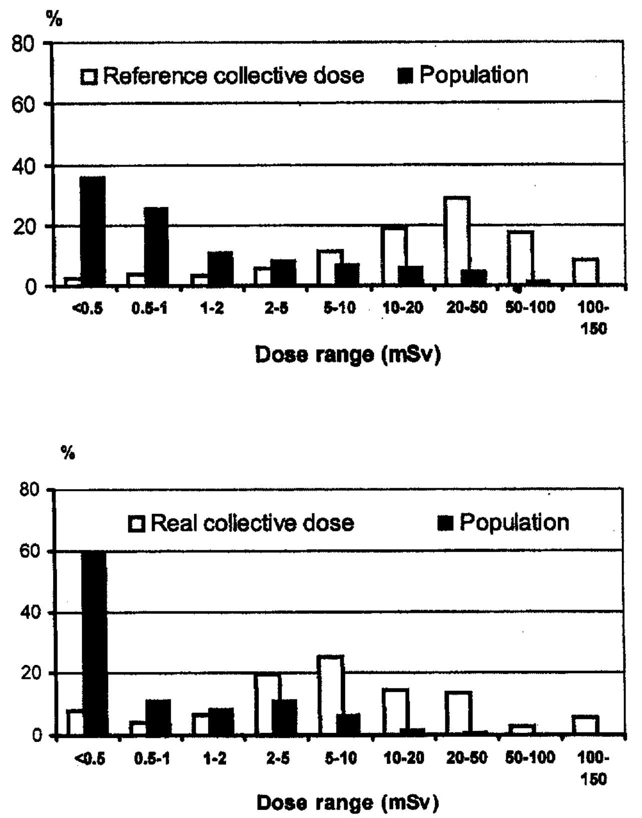

Fig. 7. Percentage distributions of collective ingestion dose and population according to intervals of average dose. Reference and real doses are in the upper and lower parts of the figure, respectively.

Table 12. Collective dose countermeasure efficiency, and averted collective dose, for the 12-y period following the Chernobyl accident for different oblasts of Ukraine.

Oblast	Population	Averted collective dose	Collective dose countermeasures efficiency (dimensionless)
Zhitomir	877,320	2,000	2.5
Kyiv	1,282,730	1,300	1.8
Rivne	751,590	4,700	3.0
Three Oblasts	2,911,640	8,000	2.5

contamination of plants and the late start of the ^{137}Cs-monitoring campaign.

The large variance of both the reference and real doses underlines the need for a stochastic dose-assessment model, for which work is underway. This current report shows that real doses are smaller than reference doses, and the difference has been attributed to the effectiveness of countermeasures. However, the uncertainty of the countermeasure-effectiveness function has not yet been fully assessed. A sound analysis of this problem will hopefully stimulate useful discussions about appropriate strategies to reduce ingestion doses following any possible future large-scale nuclear accident.

As mentioned in the introduction, since 1990 all settlements in the contaminated territory of Ukraine are included in a government program of comprehensive dosimetric passportization. The total dose estimated for each settlement includes annual and accumulated dose both from internal exposure from the consumption of foods and from external gamma exposure. The external doses have been calculated according to an official methodology (Likhtarev et al. 1998), which also contains the model used here for internal doses. A preliminary analysis of the collective dose from both internal and external exposure in the rural settlements of Zhitomir, Kyiv, and Rivne Oblasts shows that the collective internal dose accumulated up to 12 y after the accident is, on average, 51% of the total collective dose.

CONCLUSION

- The phenomenological model of Likhtarev et al. (1996a), which considers dose from the ingestion of radiocesiums, has been expanded in coverage to larger geographic areas in northern Ukraine, all age groups, and to 12 y following the Chernobyl accident;
- Two separate calculations of dose are considered: the reference dose, which is based on the concentration of ^{137}Cs in milk; and the real dose, which is based on measurements of ^{137}Cs-body burdens in humans;
- Individual and collective reference and real doses from the ingestion of radiocesiums have been calculated for about 3 million residents in Ukraine for 12 y post accident. About 60% of the considered individuals had real doses of <0.5 mSv, and about 1% had real doses in excess of 20 mSv. The 12-y real collective effective dose is estimated to be 5,300 person-Sv;
- The collective dose that was averted due to countermeasures is estimated to be 8,000 person-Sv; and
- The phenomenological model is based upon integrative concepts that are normalized to the ^{137}Cs activity per unit ground area and the soil-to-milk transfer parameter. The model is considered to be of global form and to be universal in nature and future application.

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APPENDIX

Mathematical procedure to estimate real milk equivalent, $w^{h}_{i,m}$, for the years 1986–1990

The following data sets are available for the years 1987–1990: For Rivne Oblast there are verified results of both ^{137}Cs in milk and WBC measurements; for Zhitomir and Kyiv Oblasts only the results of WBC measurements are reliable. Therefore, the values of $w^{h\tau}_{i,m}$ for 1987–1990

Table A1. Ratio of real milk equivalent in Kyiv or Zhitomir Oblasts to that in Rivne Oblast for different age groups in 1991–1996.

Oblast	Age group (y)	Value	Years 1991	1992	1993	1994	1995	1996	1991–1996
$C_{Kv/Rv,i}$ (Kyiv/Rivne)	≤7	GM	1.3	0.9	1.1	0.2	2.3	—	1.2
		GSD	3.3	1.4	7.5	3.3	2.1	—	3.4
	7–18	GM	1.7	1.3	1.1	—	2.2	—	1.9
		GSD	3.3	1.6	2.4	—	2.2	—	2.4
	≥18	GM	1.8	1.1	1.9	1.4	1.4	—	1.4
		GSD	3.3	1.8	3.2	2.7	2.3	—	2.4
$C_{Zh/Rv,i}$ (Zhitomir/Rivne)	≤7	GM	0.9	—	1.8	0.5	2.2	1.9	1.8
		GSD	2.5	—	5.0	2.8	4.3	4.1	3.9
	7–18	GM	1.0	—	1.3	0.4	2.5	1.7	1.9
		GSD	3.2	—	1.4	3.2	3.3	4.2	3.6
	≥18	GM	0.9	—	1.7	0.7	2.0	2.2	1.9
		GSD	2.8	—	1.5	2.6	3.1	3.7	3.3

Table A2. Evaluated values of the numerator and denominator in eqn (A2) and of the real milk equivalent, $w^{h}_{i,m}$, for three age groups of population in Rivne Oblast in 1986–1989. No. is the number of measurements.

Year	Age group (y)	$\lambda_{b,i}\,Q^{\tau}_{i}\,(\sigma_0 \times k^0_m)^{-1}$ (L d^{-1}) No.	GM	GSD	$c_m\,(\sigma_0 \times k^0_m)^{-1}$ (Dimensionless) No.	GM	GSD	$w^{h,\tau}_{i,m}$ (L d^{-1}) GM	GSD
1986[a]	≤7	36	3.19	2.49	74	0.14	3.00	15.2	3.89
	8–17	60	1.95	2.14				9.30	4.25
	≥18	311	2.13	2.25				10.1	3.61
1987	≤7	83	0.74	2.63	477	1.38	3.30	0.39	4.65
	8–17	394	0.56	2.36				0.30	4.33
	≥18	696	0.55	3.02				0.29	5.03
1988	≤7	1197	0.31	3.37	555	1.47	2.67	0.17	4.76
	8–17	3428	0.55	3.43				0.29	4.75
	≥18	2584	0.61	3.89				0.33	5.45
1989	≤7	956	0.39	3.16	1148	1.79	2.97	0.18	4.80
	8–17	2737	0.45	3.36				0.21	5.15
	≥18	4802	0.24	4.28				0.11	6.21

[a] For 1986, WBC and milk measurements are normalized to ^{137}Cs activity per unit area only.

for Zhitomir and Kyiv Oblasts were estimated with a procedure different from that used for estimation of $w^{h\tau}_{i,m}$ in 1991–1996. This procedure consists of three steps:

Step 1. Calculate the ratio of $w^{h\tau}_{i,m}$ for Kyiv and Zhitomir Oblasts to that in Rivne Oblast in 1991–1996. As indicated in Table 6, the values of $w^{h\tau}_{i,m}$ calculated for each oblast in 1991–1996 vary from year to year and from age group to age group, but variations with time are similar. In fact, the ratios of values of $w^{h}_{i,m}$ for oblast to oblast for the same age group hardly vary during the entire period. For this reason, it is assumed that for each group a ratio of the absolute values of real milk equivalent does not change too much during 1991–1996 for all τ-th years:

$$\frac{(w^{h,\tau}_{i,m})\,Kv}{(w^{h,\tau}_{i,m})\,Rv} = C_{Kv/Rv,i} \cong \text{Constant}$$
$$\frac{(w^{h,\tau}_{i,m})\,Zh}{(w^{h,\tau}_{i,m})\,Rv} = C_{Zh/Rv,i} \cong \text{Constant}, \tag{A1}$$

where τ indicates 1991, . . . ,1996, and indexes Kv, Rv, and Zh refer to the parameters for Kyiv, Rivne, and Zhitomir Oblasts, respectively.

The assumption in eqn (A1) allows the use of only one value each for $C_{Kv/Rv,i}$ and $C_{Zh/Rv,i}$ for Kyiv and Zhitomir Oblasts for the whole time interval of 1991–1996 for each age group. The actual values of $C_{Kv/Rv,i}$ and $C_{Zh/Rv,i}$ for 1991–1996 are provided in Table A1.

Step 2. Estimate $w^{h}_{i,m}$ for Rivne Oblast in 1987–1989. Although there was extensive monitoring of milk and body burdens in Rivne Oblast in 1987–1989, there were no simultaneous measurements of both. Therefore, measurements of Q^{τ}_{i} and c^{τ}_{m} in each settlement in year τ were standardized to the ^{137}Cs activity per unit area, σ_0, and to the soil-to-milk transfer factor, k^0_m, of that particular settlement. Then the value $w^{h\tau}_{i,m}$ for every τ year was estimated according to

$$w^{h,\tau}_{i,m} = \frac{\lambda_{b,i}Q^{\tau}_{i}}{\sigma_0 k^0_m}\cdot\left[\frac{c^{\tau}_{m}}{\sigma_0 k^0_m}\right]^{-1}, \tag{A2}$$

where $Q_i^\tau \times [\sigma_0 k_m^0]^{-1}$ = Average ^{137}Cs-body burden for members of the i-th age group for the τ-th year normalized to σ_0 and k_m^0 of the settlement of residence, and $c_m^\tau \times [\sigma_0 k_m^0]^{-1}$ = Average concentration of ^{137}Cs in milk for the τ-th year normalized to σ_0 and k_m^0 for settlements where such measurements were carried out.

Calculated values of the numerator and denominator of eqn (A2) for Rivne Oblast for 1987–1989, as well as values of $w_{i,m}^{h\tau}$, are provided in Table A2.

Step 3. Estimate $w_{i,m}^{h}$ for Kyiv and Zhitomir Oblasts in 1986–1990. As mentioned above, there is not enough information for Kyiv and Zhitomir Oblasts to obtain a direct assessment of $w_{i,m}^{h}$ in 1987–1989 by eqn (11). Although the assumptions of eqn (A1) can be verified only for 1991–1996, the assumption of the time independence of $C_{Kv/Rv}$ and $C_{Zh/Rv}$ was applied to the entire 10-y period, including 1986–1990. Later the value $w_{i,m}^{h\tau}$ for the i-th age group of Kyiv and Zhitomir Oblasts in 1987–1989 was calculated as

$$\begin{aligned}(w_{i,m}^{h,\tau})\,Kv &= (w_{i,m}^{h,\tau})\,Rv \times C_{Kv/Rv,i},\\ (w_{i,m}^{h,\tau})\,Zh &= (w_{i,m}^{h,\tau})\,Rv \times C_{Zh/Rv,i}.\end{aligned} \tag{A3}$$

■■